SMC-TR-96-13

AEROSPACE REPORT NO.
TR-95(5530)-3

Ultrasonic Inspection of Titan IV Stage I Baffles

1 March 1996

Prepared by

J. P. NOKES
Mechanics and Materials Technology Center
Technology Operations

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Space Systems Group

THE AEROSPACE CORPORATION
El Segundo, California

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-93-C-0094 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by S. Feuerstein, Principal Director, Mechanics and Materials Technology Center.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Jeffrey L Fran

~~J. B. Sovey, Col. USAF~~
~~SMC/ME~~

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
1 March 1996

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Ultrasonic Inspection of Titan IV Stage I Baffles

5. FUNDING NUMBERS
F04701-93-C-0094

6. AUTHOR(S)
J. P. Nokes

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Aerospace Corporation
Technology Operations
El Segundo, CA 90245-4691

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-95(5530)-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Missile Systems Center
Air Force Materiel Command
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
SMC-TR-96-13

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The first-stage Titan IV engine employs a set of seven CRES 347 stainless-steel baffles mounted to the injector for protection against combustion instabilities. Recent baffle design changes resulted in the failure of several baffles during engine acceptance testing. These failures generated concerns about the structural integrity of the new baffle design, which was employed in the construction of a number of engines, including those of the Titan IV K-23 vehicle, which was on a Cape Canaveral Air Force Station (CCAFS) launch pad. A Finite Element Model (FEM) was used to evaluate the baffle structure under extremes in both thermal and pressure loading. The FEM analysis indicated that poor-quality baffles would begin to debond at the braze joints during engine acceptance testing. Baffle failure during flight could result in significant performance degradation, leading to mission failure. To identify marginal baffles, a NonDestructive Evaluation (NDE) technique sensitive to small (< 0.1-in.) debonds in the baffle braze joints was needed that could be applied to post-fired baffles in installed engines. Such a technique was developed at The Aerospace Corporation.

Laboratory tests revealed that ultrasonic techniques could provide the necessary flaw resolution while being suitable for a field inspection of the engines. Additional effort was then applied toward determining the detection limits for the ultrasonic inspection of the baffle assembly, as well as providing baseline test procedures and tooling. This was followed by additional tooling development and modification performed in cooperation with engineers at Aerojet Corporation. Prior to the K-23 inspection, the procedures were verified on production hardware at the Aerojet facility in Sacramento, CA. The baffles on the K-23 vehicle engines (S/N 1030 & 1031) were inspected on March 1–2, 1995. The ultrasonic inspection revealed no measurable debonds at the braze joints.

14. SUBJECT TERMS
Ultrasonic, Baffle failure, Nondestructive evaluation

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Contents

Figures

1. Introduction

Each combustion chamber assembly on the Titan IV LR87-AJ-11 engine has seven CRES 347 stainless-steel baffles radially mounted to the face of the injector to control combustion instabilities. Some of the primary elements of the engine, including the baffles, are shown in the exploded view of the LR87 engine presented in Figure 1.

Each baffle assembly consists of a set of 16 spacers or ribs sandwiched between two face plates. Oxidizer flows through the channels formed by the ribs to regeneratively cool the baffle. Additionally, there is fluid film cooling over a portion of the baffle. The main elements and regions of a baffle assembly are identified in Figure 2.

In 1990, Aerojet modified the baffle design by changing from a two-piece to a three-piece assembly. In the two-piece baffle, the oxidizer channels were milled into one of the faceplates so that braze joints were required on one side of the baffle only. In the three-piece design, the milled channels were replaced with a separate rib plate that was brazed to both faceplates, as indicated in Figure 2. Machining operations were performed to remove excess rib material and prepare the faceplates for welding. A tip strip was then welded into place, and the completed baffle was evaluated using a through-transmission ultrasonic technique. This NonDestructive Evaluation (NDE) technique is sufficient for inspecting the rib braze joints before the completed baffle is welded onto the injector surface.

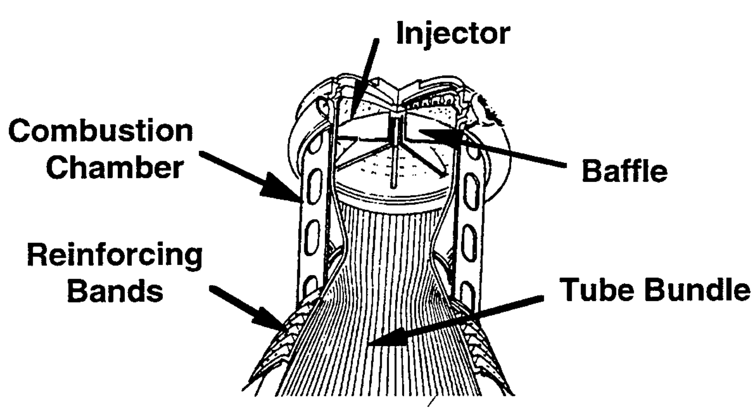

Figure 1. Location of baffles in the assembled Titan IV LR87-AJ-11 engine.

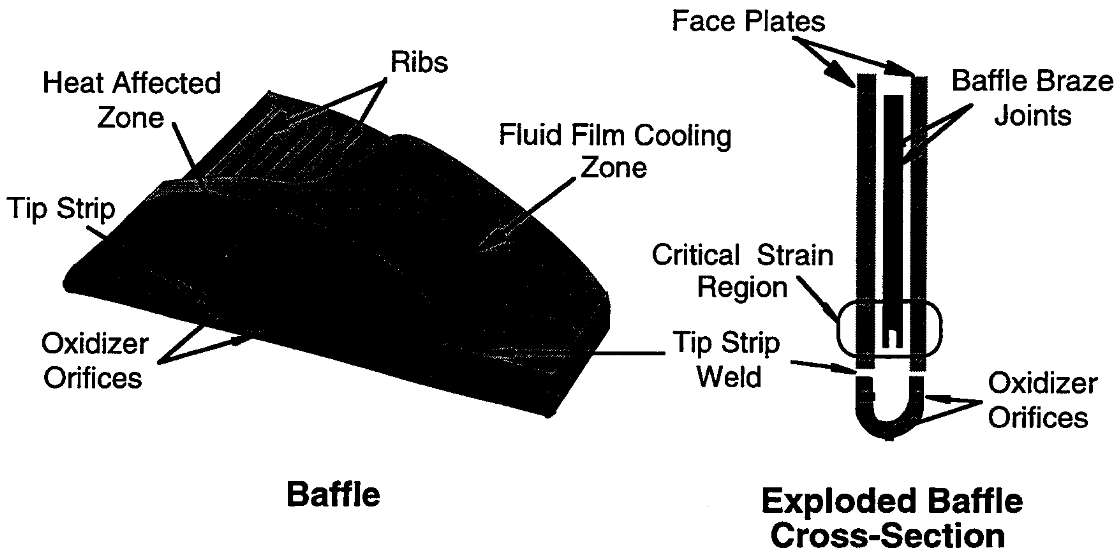

Figure 2. Schematic of Titan IV injector baffle.

Recent problems in the manufacturing process resulted in the failure of several three-piece baffle assemblies during engine acceptance testing. Acceptance testing for the Titan IV LR87 engines consists of firing the engine for approximately 21 seconds. The conditions produced during the firing provide an effective proof test of the engine assembly. Where there were failures, the baffles bulged and split at the braze joints, with the faceplates separating from the ribs. These failures make suspect those engines fitted with the three-piece brazement. To address concerns associated with the new baffle design, a Finite Element Model (FEM) was generated by the Aerospace structures group to evaluate the baffle design under the maximum expected thermal and pressure loading. The analysis identified the critical region to be the rib tips in the Heat Affected Zone (HAZ), as indicated in Figure 2. The HAZ is below the fluid film cooling region and is characterized by discoloration of the baffle due to extreme temperatures. The FEM study suggested that for a baffle with marginal strength, a test firing of the engine would create debonding along the braze joints at the rib tips in the HAZ. Subsequent test firing or the actual launch of a marginal baffle could then cause the debonds to grow beyond the critical flaw size, leading to total failure of the braze joint. The critical flaw size in the HAZ was found to be on the order of 0.10 in. A secondary concern is debonds occurring in other areas of the baffle. It was felt that while these flaws were not likely to initiate a baffle failure, they might be indicative of a marginal structure. Away from the HAZ, the minimum detection resolution was specified to be 0.125 in. To ensure that the three-piece baffles currently in the fleet are structurally sound, an NDE technique sensitive to small (< 0.1-in.) debonds in the baffle braze joints was needed that could be applied to post-fired baffles in installed engines. Such a technique was developed at The Aerospace Corporation. Of particular immediate interest were the engines installed in the K-23 vehicle (S/N 1030 and 1031), currently on the launch pad at Cape Canaveral Air Force Station (CCAFS).

A laboratory survey of NDE techniques revealed that Ultrasonic Testing (UT) could provide the necessary flaw resolution while being adaptable to field inspection of the engines. [It should be noted that while ultrasonic techniques can be used to detect joint separations (debonds), no information on the strength of a braze joint is obtained.] The effort was then expanded to meet the needs and restrictions of debond detection within the combustion chamber assembly. Additional effort was applied toward determining the detection limits for debonds both in the center of the baffles and the rib tips, as well as providing baseline test procedures and tooling. This was followed by additional tooling development and modification performed in close cooperation with engineers at Aerojet Corporation.

2. Experimental Results

Evaluating the proposed baffle inspection technique required a test standard with known flaws. For the initial calibration standard, a two-piece baffle was obtained from the Titan Program Office. This two-piece baffle was used for initial testing only. Debonds were simulated in the baffle by removing material from selected ribs with an end mill. For the preliminary calibration standard, two 0.050-in. sections were removed from a rib in the central portion of the baffle. In addition, the lengths of three ribs were reduced by 0.035, 0.050, and 0.080 in. In the initial studies, a Panametrics, 15-MHz, focused pencil-probe transducer was employed in conjunction with a Panametrics Model 5052 pulser/receiver and a Fluke Model 97, 50-MHz oscilloscope. An Amdata Model 4020 X-Y scanner was used to accurately position the UT transducer on the baffle standard, as depicted in Figure 3.

The Panametrics focused transducer has a 0.080-in.-diam. footprint and provided the best flaw resolution of the readily available commercial transducers. A disadvantage with the small contact area is a greater susceptibility to rocking of the transducer and associated signal loss. The rocking in the pencil probe was mitigated to some extent with a Teflon™ tool that held the sensor in the proper position. Examples of typical ultrasonic signals from a rib inspection are shown in Figures 4 and 5. The waveform in Figure 4 is an example of the echo return from a rib in intimate contact with both the front- and back-faceplates. The sound travels through the front-faceplate, rib, and back-faceplate and then is reflected by the back-faceplate/air interface producing an echo at the UT receiver. The round-trip time-of-flight for each pulse provides a very accurate measure of the sound path in the material. Debonds provide a reflecting surface within the baffle altering the time at which the UT echo will appear. So, by evaluating the round-trip time-of-flight for a UT pulse, not only can one detect a debond, but one can also determine the faceplate on which it appears. For example, the back-faceplate/air-interface echo from a fully bonded baffle will appear later in time than that from a debonded baffle/back-faceplate interface.

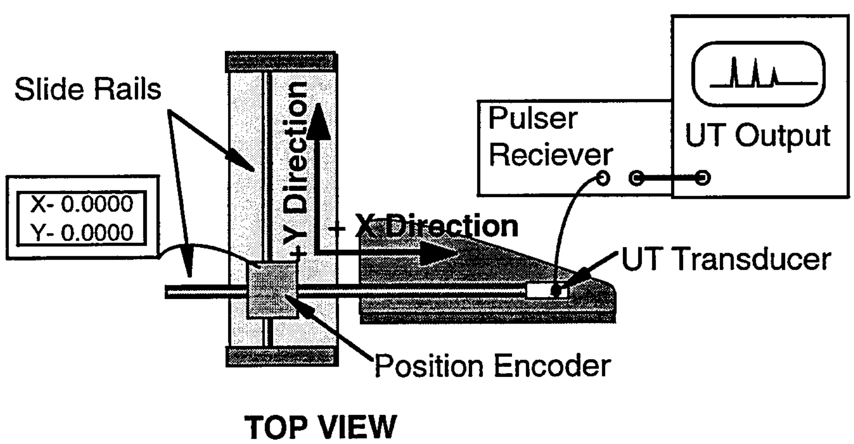

Figure 3. Schematic diagram of the bench top scanner used for the initial testing of the ultrasonic baffle inspection procedures and equipment.

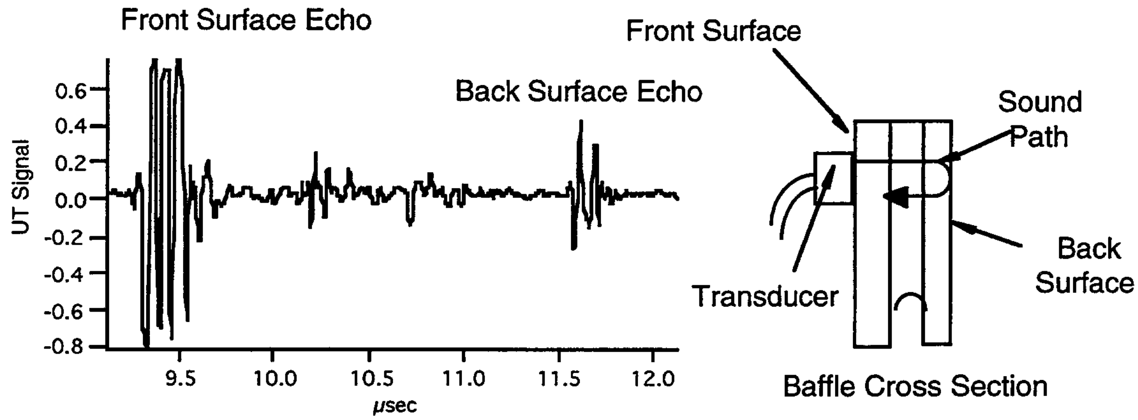

Figure 4. Ultrasonic signal from a baffle rib indicating a good contact between both face plates and the rib.

The signal displayed in Figure 5 is typical of the return that would be expected from a front-faceplate/baffle debond. In this case, the ultrasonic pulse travels a path that is equivalent to twice the thickness of the faceplate. As a result, the waveform in Figure 5 is also characteristic of the signal obtained from a position on the baffle between ribs since the normal faceplate/air interface is indistinguishable from that of the faceplate/baffle with a debond.

While investigating simulated baffle debonds, difficulties were noted in evaluating debonds at the rib tips. Over the majority of the baffle area, debonds in an individual rib could be located and sized by detecting the edges of the debond area. However, at the rib tips, it was difficult to determine for a particular rib whether the displayed signal indicated an actual debond or simply that the transducer had moved past the end of the rib. The difficulty was exacerbated when an inspection was made in

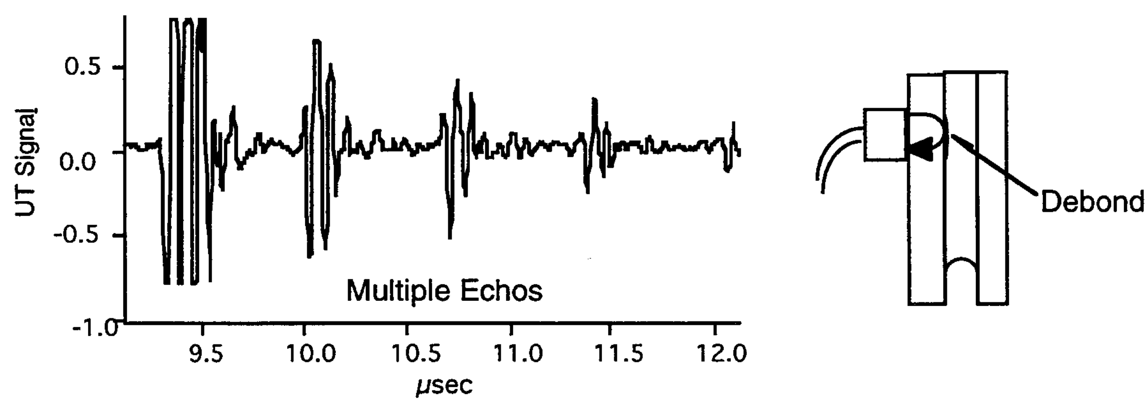

Figure 5. Ultrasonic signal showing the multiple reflections typical in the front surface debond.

the combustion chamber without the visual cues found on the bench top. To meet the stated (< 0.10-in.) resolution requirements, a different approach was taken for inspecting the rib tips. Instead of evaluating each rib individually, a horizontal scan was implemented that compared an individual rib tip to the other 15 ribs, as shown in Figure 6. A Teflon™ tool was used to position the transducer at the desired elevation on the baffle. The fixture allowed for the centerline position of the transducer to be adjusted to account for variations in the hardware. Using this scanning approach and the focused transducer, rib debonds on the order of 0.035 in. could be detected.

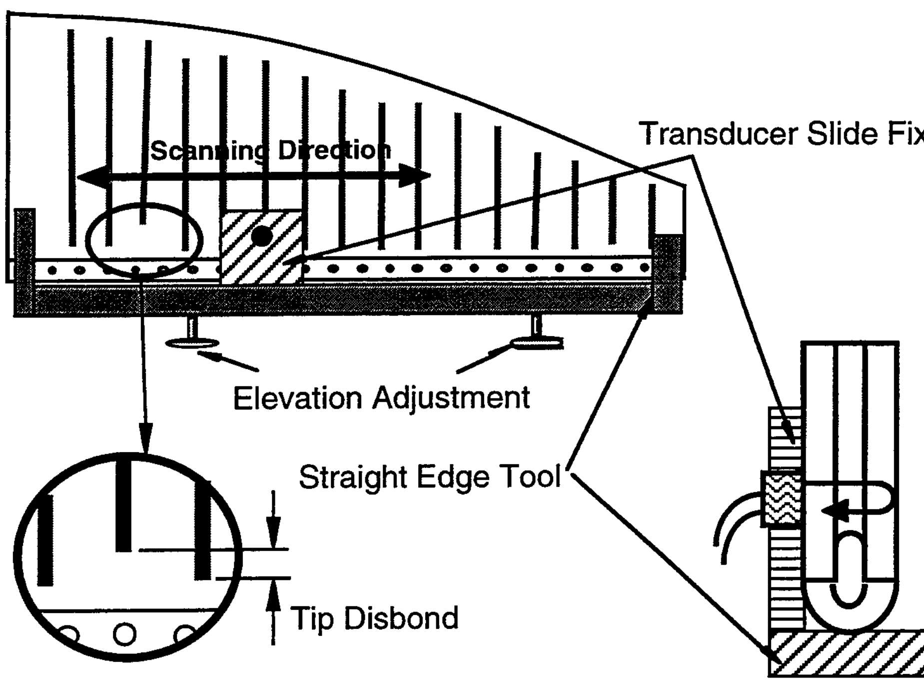

Figure 6. Ultrasonic Inspection near the rib tips.

3. Test Procedure

The data gathered during proof-of-concept investigations at Aerospace was used to develop inspection procedures that could be applied to the assembled combustion chamber at the launch site. Inspection of an assembled engine requires that the inspector reach up approximately 22 in. past the throat of the engine, which has a diameter of 15.25 in. During initial conversations with the NDE engineers at Martin Marietta and Aerojet, an inspection procedure was proposed and adopted where a transducer guide or template was to be used to aid in positioning the ultrasonic probe over the ribs. The guide served the same function that the X-Y scanner had provided in the laboratory—a means for locating the transducer on the baffle. A template was built with slots cut into Plexiglas faceplates, as shown in Figure 7. During a faceplate/rib interface inspection, the ultrasonic transducer was guided down the length of the slots. Because of clearance constraints within the combustion chamber, one rib from each end of the baffle was not accessible for inspection. To aid in locating any UT indications, scribe marks were located on the template in 0.50-in. increments.

Friction held the guide onto a baffle for the initial fit up. The tool was then adjusted to center the slots over the ribs. If necessary, the template could be snugged down further using the position lock identified in Figure 7. The inspection was performed using a Krautkramer Branson, Model CL204 thickness gauge with a 0.125-in.-diam., 20-MHz transducer. During development of the inspection procedure at Aerojet's Sacramento facility, the aforementioned equipment was found to provide the 0.125-in. debond resolution required in the "non-critical" rib regions. Use of the thickness gauge and slightly larger transducer, as opposed to the focused transducer used in laboratory tests, made positioning of the transducer easier for the inspector, particularly while working in the combustion chamber. The Model CL204 thickness gauge automatically converts the time-of-flight information from the received echoes into a thickness measurement. Using this equipment on a baffle having a nominal

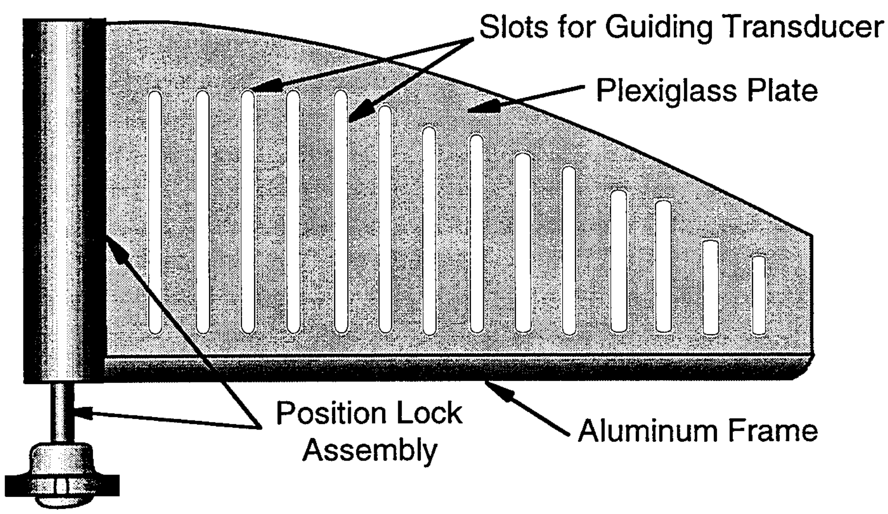

Figure 7. Transducer guide for baffle inspection.

thickness of 0.25 in. would result in a thickness measurement of (1) 0.25 in. if both faceplates are properly bonded, (2) 0.17 in. if the back-faceplate is debonded, and (3) 0.08 in. if the front-faceplate is debonded.

The template allowed the inspector to make good measurements for the majority of the rib/faceplate interfaces while working within the engine. However, as previously mentioned, the template did not address the inspection problems at the rib tips. The rib tip inspection procedure and tooling were finalized while working in conjunction with Aerojet NDE engineers at their Sacramento facility. An important part of preparation for the tip inspection was fabrication of the calibration standard shown in Figure 8 from a three-piece production baffle. As indicated in the figure, 0.0625 to 0.25 in. of material was removed from several of the tips to simulate front-faceplate debonds. In addition, the back-faceplate was removed for two ribs to simulate back surface debonds of 0.125 and 0.0625 in. As mentioned above, a Panametrics focused probe used in conjunction with a pulsar/receiver and oscilloscope was a successful combination during laboratory tests. By comparing measurements on the calibration standard, it was found that the same probe used in the coarse inspection could be substituted for the Panametrics focused probe while maintaining tip resolutions of better then 0.1 in. Using the tools and procedures developed at both the Aerospace and Aerojet facilities, the baffles on the K-23 vehicle were inspected on March 1 and 2, 1995, at CCAFS. No UT indications were reported during the K-23 baffle inspection.

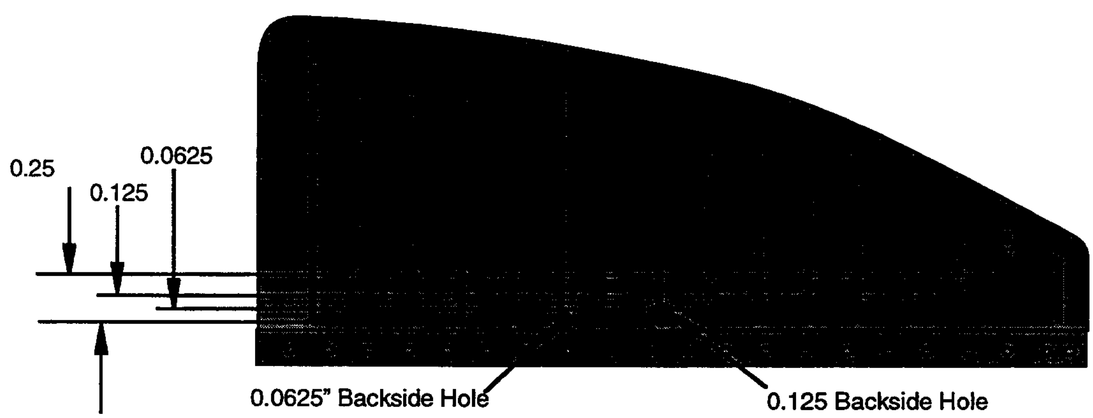

Figure 8. Baffle calibration standard used during the baffle inspection procedure development and the K-23 vehicle inspection.

4. Conclusions

Using standard ultrasonic measuring techniques in conjunction with specialized probe positioning tools, an effective inspection procedure has been developed for the Titan IV Stage I combustion chamber baffles. Using a simple thickness gage and 0.125-in.-diam. UT probe, a debond resolution of approximately 0.125 in. was demonstrated. By substituting a specialized pulser/receiver and oscilloscope for the Krautkramer Branson, Model CL204 thickness gauge, the detection resolution was enhanced to < 0.100 in. The best flaw resolution, approximately 0.035 in., was found using a focused probe with a high-frequency pulser/receiver and oscilloscope. The baffle inspection was carried out in two parts, a coarse-resolution (0.125-in.) scan of the baffle and a high-resolution (<0.1-in.) scan of the rib tips. For the high-resolution inspection, uncertainties in the location of the rib tips were minimized by comparing each rib tip to its neighbors. Following development of the inspection techniques, the engines (S/N 1030 & 1031) on the Titan IV K-23 vehicle were inspected. No indications of debonds were found.

TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

Electronics Technology Center: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, Micro-Electro-Mechanical Systems (MEMS), and data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; development and analysis of thin films and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; development and evaluation of hardened components; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion; spacecraft structural mechanics, spacecraft survivability and vulnerability assessment; contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; lubrication and surface phenomena.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.